9.—The high-grade metamorphic and associated igneous rocks of Mt Bakewell, near York, Western Australia.

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Abstract

The Mt Bakewell area consists of a complexly folded sequence of high-grade metamorphic rocks forming part of the Early Precambrian Jimperding metamorphic belt. Granitic gneisses, cordierite-bearing rocks, quartzites, metajaspilites, and basic granulites have been derived from arkoses or greywackes, shales, quartz sandstone, iron formation, and intercalated basaltic sills or flows respectively, under syntectonic lower granulite facies conditions. Ultrabasic bodies emplaced after the main period of metamorphism have recrystallised under greenschist facies conditions. Three sets of folds—representing at least two, and possibly three, successive deformation phases of the orogenic cycle—are recognised. Almost recumbent isoclinal folds (formed during metamorphism) with axial planes dipping NE. have been warped into a broad NE.-plunging synform, and overprinted by later mild E.-W. crossfolding. A progressive increase in metamorphic grade from amphibolite facies in the west to granulite facies in the east is recognised in the Jimperding metamorphic belt, and three zones of metamorphism have been tentatively established. The metamorphic rocks have been intruded firstly by adamellite, then by dolerite dykes, the latter divisible into three categories all derived from tholeiitic magma.

Introduction

The area under review, measuring 7 square miles, is near York, the centre of a wheat and sheep farming district situated on the banks of the Avon River, 60 miles by bitumen highway from Perth. Mt Bakewell, the major physiographic feature in the area, is 3 miles north of York railway station. The area is part of the West Australian Precambrian Shield and is composed largely of high-grade metamorphic rocks of the Jimperding metamorphic belt (see Figure 1).

The aim of this investigation was to examine the petrology and structure of the Precambrian metamorphic and igneous rocks encountered in the area. Chain and compass and plane table surveys were carried out by students (including the author) from the Geology Department of the University of Western Australia under the direction of members of Staff during 1950-52 and 1960-61. The mapping was completed by the author in 1963 using pace and compass. Nearly 140 specimens were collected and sectioned for the petrological work. Specimen numbers cited in the text refer to the collection of the Geology Department of the University of Western Australia. Field locations are stated as 6-figure co-ordinates from the accompanying geological map (folding map at end).

Previous Investigations

Similar geological investigations have been carried out in nearby exposures of the Jimperding metamorphic belt at Malkup (Cole and Gloe 1940), Toodyay (Prider 1944), Lawnswood (McWhae 1948), Hamersley Siding (Johnstone 1952), Quartz Hill (Willmott 1955), Mt Dick (Pidgeon 1961), Whitfields Hill (Brophy 1963), Needling Hills (Danielson 1963) and Nunyle (Elkington 1963). A dyke complex in the northern part of the area at present under review was the subject of a detailed study by Martin (1961), and Gregson (1961) has examined the magnetic rocks occurring on the western slopes of Mt Bakewell.

Physiography

The topography of the area is closely related to the underlying geology. The gneisses have weathered to form gently undulating country typical of the Wheat Belt. Quartzite, being more resistant to erosion, stands well above the general level, and forms an east-west trending range, or cuesta, 2½ miles long with a gentle northern dip-slope and a steep southern escarpment which slopes down to the flood plain of the Avon River (Figure 2). Mt Bakewell, with an elevation of 1501 feet above sea level, and about 700 feet above the surrounding country, is the highest point of this range. At its western end the range swings northwards to a NNW.-SSE. trend as a result of a change in the strike of the quartzite. The physiographic prominence of the range then gradually diminishes over a distance of 2½ miles as it grades to the north into a line of discontinuous ridges, and eventually fades into a broad alluvium-filled valley which drains eastward into the Avon River. In places the quartzite is capped by erosion remnants of Tertiary laterite forming gently sloping mesas.

Numerous consequent streams flow from the quartzite ridges, at the feet of which wide alluvial flats have formed as a result of active erosion. The streams are commonly deeply incised into their alluvium. Some of the gullies on the slopes of the quartzite ridges contain rock "glaciers" of quartzite talus.

General Geology

The area under consideration consists of a complexly folded sequence of Precambrian high-grade metamorphic rocks forming part of the Jimperding metamorphic belt, with numerous unmetamorphosed acid and basic igneous intrusions. The major rock type is granitic

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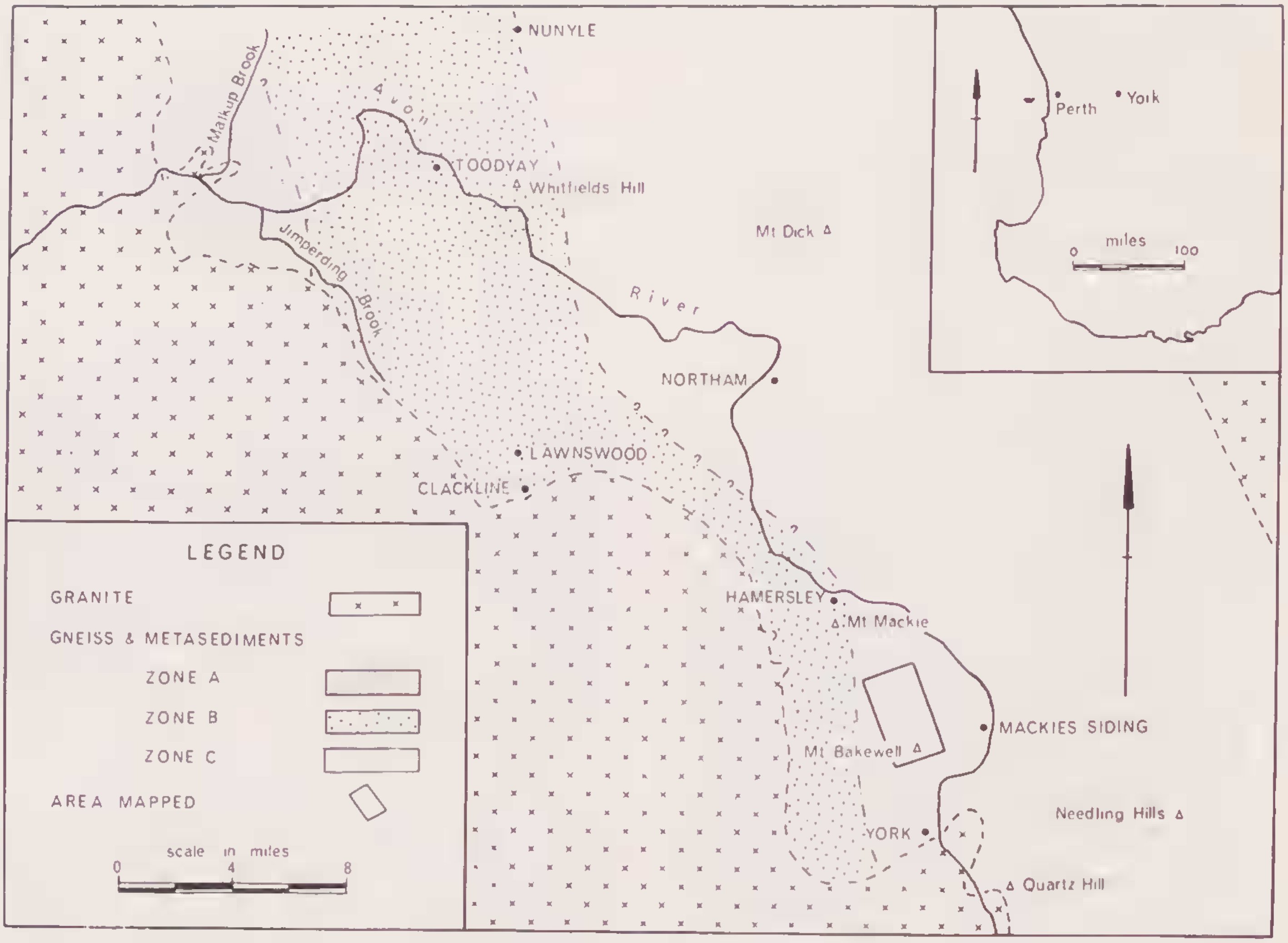

Figure 1.—Geological sketch map of part of the Wheat Belt region of Western Australia showing the location of the area mapped. The division of the metamorphic rocks into zones is proposed in a later section of this paper.

Figure 2.—View of Mt Bakewell from the west, showing the gentle northern dip-slope and the steep southern escarpment.

gneiss, which is commonly garnetiferous, and contains conformable bands and lenses of quartzite, basic granulite, metajaspilite, cordierite-bearing rocks, and metamorphosed ultrabasics. The last group includes serpentinites, tremolite-actinolite rocks, and talc rocks.

Late or post orogenic adamellite instrusions occur as dykes up to 1 chain wide, trending N.-S. The contacts are sharp and undoubtedly intrusive, but chilled margins and contact metamorphism were not observed.

Emplacement of numerous dykes and rare sills of tholeiitic dolerite followed the adamellite intrusions. Martin (1961) has studied in detail a dyke complex in the northern part of the area at present under review, and has presented a classification of the dolerites found there. The present author, after a wider though less detailed survey, has modified Martin's nomenclature and age relationships, and tentatively proposes the following classification:

(a) Altered quartz dolerite.

(b) Quartz-orthopyroxene dolerite and related basaltic plagioclase-augite-phyric dolerite.

(c) Basaltic plagioclase-phyric dolerite.

The altered quartz dolerite, occurring as dykes up to 5 chains wide trending predominantly NNW., is older than the other dolerites except a few of the basaltic plagioclase-phyric intrusions. Quartz-orthopyroxene dolerite forms NW.-trending dykes up to 5 chains wide, which cut—and are therefore younger than—the altered quartz dolerites. The quartz-orthopyroxene dolerite intrusions have chilled margins of basaltic plagioclase-augite-phyric dolerite. Narrow dykes identical with these chilled margins intrude the altered quartz dolerite, but not the quartz-orthopyroxene dolerite. The basaltic plagioclase-phyric dolerite, occurring as numerous thin dykes and sills, intrudes all the other dolerites and therefore represents the last phase of dolerite emplacement. However, at least two phases of intrusion by basaltic plagioclase-phyric dolerite have occurred, because at two localities this rock is cut by altered quartz dolerite (cf. Martin 1961).

Metamorphic Rocks

Petrography

During the course of this investigation about 150 thin sections were examined, and a detailed account of the petrography has been prepared (Stephenson 1963). Only summary descriptions will be presented in this paper.

1. The *granitic gneisses* vary from somewhat massive and granoblastic to well foliated due to the concentration of dark platy minerals in thin layers. They may be equigranular medium-grained or strongly porphyroblastic. The major minerals are usually (e.g. 50478) plagioclase (oligoclase or andesine), microcline, quartz, and biotite occurring in varying proportions. Microcline is normally crosshatched and weakly perthitic, and may occur as augen porphyroblasts. Biotite ($X =$ light brown, $Y = Z =$ dark brown or reddish brown) occurs in well oriented flakes which may be concentrated in thin bands or scattered throughout the rock. Pink garnet (almandine-pyrope; $n = 1.787 - 1.790$) is locally a major constituent and occurs mainly as large, ragged, sieve-textured porphyroblasts (e.g. 50479). Hypersthene and anthophyllite are rare. Strongly pleochroic hypersthene ($X =$ pink, $Z =$ green) is a minor constituent of 50480, which contains also quartz, garnet, microcline, biotite, and andesine. The hypersthene occurs in equant xenoblasts which partially enclose biotite flakes, simulating a subophitic relationship. Prismatic (locally fibrous) anthophyllite ($\gamma = 1.645$; $2V_{\gamma} = 70°$) is a major constituent of 50481, which contains also quartz, biotite, and andesine. A few remnants of hypersthene in the anthophyllite suggest that the amphibole formed from orthopyroxene as a result of retrograde reactions. Minor accessories in the granitic gneisses include magnetite, apatite, rounded zircon and monazite, epidote, and muscovite.

2. The *cordierite-bearing rocks* (e.g. 46687, 50482) are fairly massive in hand specimen, but in thin section they are usually gneissic due to rough concentration of biotite into bands. The normal mineral assemblage is cordierite-quartz-garnet-biotite-sillimanite. The cordierite and quartz are xenoblastic, the former strongly pinitised. Pink garnet ($n = 1.786 - 1.793$) occurs as large poikiloblasts with numerous inclusions of the other minerals. Biotite ($X =$ straw, $Y = Z =$ reddish brown) shows a preferred orientation and rare alteration to chlorite. Sillimanite is usually a minor mineral, occurring as oriented slender rods with slight alteration to muscovite. Leucoxenised ilmenite and plagioclase are normally present in small amounts. Rare accessories are zircon and monazite (with pleochroic haloes in cordierite), apatite, magnetite, and hematite. In 50483 sillimanite constitutes about 60% of the rock, cordierite and biotite making up the remaining 40%. Specimen 33930 contains the assemblage cordierite-hypersthene-quartz-biotite. The cordierite ($\beta = 1.544$) is fairly fresh, with polysynthetic twinning. The hypersthene is xenoblastic and strongly pleochroic with $X =$ pink, $Y =$ pale yellow, $Z =$ pale green; $\gamma = 1.706$ suggesting its composition is Fe_{34}.

3. The *quartzites* are medium- to coarse-grained, granoblastic, fairly pure quartz rocks (e.g. 50484, 50486). They are usually white or pale pink but the presence of appreciable chrome-muscovite imparts a green colouration. The structure varies from massive to blocky or flaggy, depending on development of bedding and jointing. Bedding surfaces commonly show a *b*-lineation due to preferred orientation of mica and sillimanite. The quartz occurs in irregularly shaped interlocking grains with sutured margins. Extinction is usually slightly undulose, and fine dusty inclusions are arranged in Boehm lamellae. Muscovite (commonly chrome-muscovite) constitutes up to 5% of the rock, occurring as well oriented flakes concentrated in thin bands defining the foliation (= bedding), and as small disseminated flakes included within the quartz. Equant grains of oligoclase and crosshatched microcline are fairly rare. Some samples contain

up to 3% sillimanite in well oriented rods commonly partially replaced by fine muscovite. Very fine, hairlike needles of rutile are abundant in nearly all specimens examined. The needles are continuous across quartz grain boundaries and may or may not show a strongly preferred orientation parallel to the megascopic lineation. The TiO_2 content of 50488 is 0.95%. Rare accessories are apatite, magnetite, hematite, rounded zircon and rutile.

4. The *metajaspilites* are finely banded, fine- to medium-grained granoblastic rocks. Small-scale folding has been developed in places, either by slumping in the original sediment or by tectonic processes during metamorphism. These rocks show great diversity in mineral assemblages reflecting variations in chemical composition (see Table 1). Quartz and magnetite are ubiquitous major constituents, and may be accompanied by either orthopyroxene or grunerite, or both. Garnet, ferroaugite, and hornblende are possible additional minerals in the orthopyroxene-bearing varieties. Feldspar is very rare.

TABLE 1

Chemical and modal analyses of metajaspilites from Mt Bakewell

	50489	50490	50492	46688
SiO_2	47·3	44·4	53·5	45·5
TiO_2	0·3	2·0	0·8	1·1
Al_2O_3	2·8	5·9	5·2	9·4
*Fe_2O_3	48·2	41·9	36·2	35·4
MgO	1·9	1·9	2·5	5·1
CaO	0·3	2·0	1·1	3·2
Na_2O	0·3	0·2	0·6	0·8
K_2O	tr.	tr.	0·1	0·2
	101·1	98·3	100·0	100·7
Modes :				
Quartz	37	30	24	25
Magnetite	28	29	14	20
Eulite	35	25	41	42
Ferroaugite		15		3
Hornblende		1		3
Garnet			11	7
Andesine			7	
Grunerite			3	

* Total iron as Fe_2O_3.

Analyst : N. C. Stephenson. Analytical methods based on those of Davis (1961).

Quartz and magnetite are xenoblastic and show a tendency towards segregation into narrow bands. Orthopyroxene (eulite) is strongly pleochroic with X = pink, Y = yellow, Z = green; α = 1.733 - 1.745, β = 1.747 - 1.755, γ = 1.752 - 1.762; δ = 0.017 - 0.019; $2V_x$ = 63° - 77°; suggesting a composition range Fe_{70}-Fe_{80}; average Fe_{73}. Exsolution lamellae parallel to (100) are rarely well developed, and magnetite inclusions are common. Marginal alteration to finely fibrous amphibole (grunerite?) is fairly common, especially on grain margins in contact with quartz. Grunerite occurs mainly as polysynthetically twinned prismatic grains and closely associated fibrous aggregates. Almandine garnet (n = 1.804 - 1.811) occurs as irregularly shaped pink grains containing quartz and magnetite inclusions. Ferroaugite (about $Ca_{44}Mg_{26}Fe_{30}$) is pale green with β = 1.706 - 1.710, $2V_z$ = 54° - 55°, and polysynthetic twinning. Hornblende (X = yellowish green, Y = dark green, Z = dark bluish green; Z∧c = 22°; β = 1.710 - 1.713) is a minor constituent. Andesine, An_{37}, was found in one specimen only (50492). Apatite needles are very rare.

5. The *basic granulites* are fine- to medium-grained rocks with granulose texture. Rarely a preferred orientation of hornblende or biotite results in a weakly developed foliation. Banding is usually absent. The assemblage plagioclase-calcicaugite-hypersthene-hornblende ± biotite is most common. The ultramafic assemblages hornblende-calcicaugite-hypersthene ± biotite and hornblende-hypersthene ± spinel are relatively rare, and are found only in close association with the plagioclase-bearing variety.

TABLE 2

Modal analyses, optical constants and derived compositions of the major minerals in representative samples of basic and ultramafic granulite from Mt Bakewell

	50498	*50499	50502	*50503
Plagioclase	49	32		
Calcicaugite	22	13	37	
Hypersthene	16	18	8	11
Hornblende	13	35	53	85
Biotite		1		
Magnetite	tr.	1	2	1
Spinel				3
Apatite	tr.			
Plagioclase	An_{58}	An_{78}	absent	absent
X′∧010 (⊥a)	31	39		
Calcicaugite	$Ca_{43}Mg_{31}Fe_{26}$	$Ca_{41}Mg_{35}Fe_{24}$	$Ca_{44}Mg_{40}Fe_{16}$	absent
$2V_Z$	54	55	53	
β	1·703	1·702	1·692	
Hypersthene	Fe_{46}	Fe_{46}	**Fe_{32}	**Fe_{33}
$2V_X$	51		64°	71
γ	1·722	1·722	1·704	1·705
Hornblende				
$2V_X$			86	89
β	1·683	1·684	1·659	1·659

* Analysed samples. See Table 3.

** Composition derived from γ. $2V_X$ measurement indicates a lower Fe content. In all other samples γ and $2V_X$ measurements agree well.

The optical constants and optically derived compositions of the major minerals in a number of representative specimens are set down in Table 2. Plagioclase is usually unzoned labradorite, or bytownite but normal zoning has been observed. Twinning is limited to the albite and pericline laws. Calcicaugite (pale green) and hypersthene (X = pink, Y = neutral or pale yellow, Z = pale green) are more Fe-rich and Mg-poor in the plagioclase-bearing rocks than in those without plagioclase. The hornblende normally appears to be in textural equilibrium with the pyroxenes, and has the pleochroic scheme X = light brown, Y = dark brown, Z = dark greenish brown in the plagioclase-bearing rocks, and X = straw, Y = yellowish green, Z = green in rocks without plagioclase. The occurrence of biotite (X = straw, Y = Z = dark brown or reddish brown) is limited. Very dark green, almost opaque xenoblastic spinel may constitute up to 5% of rocks lacking plagioclase. Magnetite and apatite are minor accessories. Actinolite, chlorite, and talc are locally present as secondary minerals.

Chemical analyses of a plagioclase-bearing granulite and a plagioclase-free granulite are given for comparison in Table 3. It can be seen that the optically derived pyroxene compositions reflect the MgO and total iron (as Fe_2O_3) content of the rocks.

TABLE 3

Chemical analyses of basic and ultramafic granulites from Mt Bakewell compared with average Deccan basalt and olivine basalt analyses

	50499	50503	A	B
SiO_2	47·4	45·9	50·61	46·00
TiO_2	1·6	1·7	1·91	1·62
Al_2O_3	13·7	14·2	13·58	12·42
Fe_2O_3	*14·5	*11·8	3·19	0·53
FeO	nd	nd	9·92	12·72
MnO	nd	nd	0·16	0·27
MgO	4·7	12·7	5·46	11·08
CaO	15·4	9·9	9·45	10·80
Na_2O	1·2	2·2	2·60	2·64
K_2O	0·4	0·4	0·72	0·42
H_2O^+	nd	nd	2·13	0·63
H_2O	nd	nd		0·60
P_2O_5	nd	nd	0·39	0·19
	98·9	98·8	100·12	99·92

* Total iron as Fe_2O_3.

50499 Calcicaugite-hypersthene-bytownite-hornblende granulite.

50503 Spinel-hypersthene-hornblende granulite.

Analyst : N. C. Stephenson.

A Average Deccan basalt (Turner and Verhoogen 1960, p. 215).

B Olivine basalt (Turner and Verhoogen 1960, p. 190).

6. The *ultrabasic rocks*. Three main varieties—namely serpentinite (46811, 50508), tremolite-actinolite rocks (50513-50515) and talc rocks (34497, 50516)—have been recognised.

The serpentinites are dark green, massive, fine-grained rocks composed mainly of antigorite with characteristic mesh texture. Larger flakes of colourless chlorite with Berlin blue interference colour are widely scattered. Abundant magnetite is distributed along cracks and around relict grain boundaries, but the shapes of the latter are not sufficiently diagnostic to permit confident identification of the primary mineral assemblage. Slight replacement by pale brown chalcedony and incipient alteration to fine talc are fairly common. Cross-fibre chrysotile veins are small and rare.

The tremolite-actinolite rocks are pale green and commonly weakly schistose due to the orientation of rod-like amphibole prisms. The amphibole varies from actinolite, Fe_{30} (γ = 1.649; $2V_x$ = 88°; X = colourless, Y = Z = very pale green) to tremolite, Fe_{17} (γ = 1.639; $2V_x$ = 71°; colourless). Fine disseminated magnetite is common. Tremolite rocks show strong alteration to talc. Increasing iron content of the amphibole is associated with a decrease in the degree of alteration, and pale green chlorite becomes the dominant alteration product, with talc subordinate.

The talc rocks are massive, pale grey, fine-grained and soft. They consist of a fine aggregate of talc, rare phlogopite (X = colourless, Y = Z = yellowish brown) and abundant magnetite distributed around relict grain boundaries in the same manner as in the serpentinite, suggesting derivation from the latter rock.

Remnants of primary minerals were found in one sample only—namely 44626, a talc-cummingtonite-bearing orthopyroxenite. This rock is composed mainly of bronzite, Fe_{13} (γ = 1.680) in crystals up to 15 mm long, fairly extensively replaced by talc. Subhedral, pale green cummingtonite of possible secondary origin is common. Minor constitutents are magnetite, chlorite, and rare antigorite pseudomorphs after olivine (?). The texture of this pyroxenite does not closely resemble the relict textures in the serpentinites and talc rocks, so the original identity of these two rocks remains uncertain.

Petrogenesis

Metamorphic Facies

Most of the rocks described above, representing widely different bulk compositions, have completely recrystallised during high-grade regional metamorphism. The ultrabasic rocks, however, belong to a distinctly lower facies and will be discussed separately later. Retrograde effects, though common, are not intense, and will also be discussed later. The possibility that the rocks have been subjected to more than one metamorphic event—apart from the events which caused the minor, easily recognised downgrading—has been considered, but in the absence of evidence to the contrary it is assumed that the high-grade assemblages represent a single major metamorphic episode. It is further believed that the recrystallisation was syntectonic, having coincided with the major period of folding, because tabular and elongate minerals are commonly oriented with respect to foliated and linear structures without showing much evidence of strain.

Neglecting obviously retrograde minerals and minor accessories, the typical assemblages encountered in the area are as follows, with assemblages and minerals of restricted occurrence shown in parentheses:

1. Granitic gneisses:
   (a) quartz-microcline-plagioclase-biotite ± garnet (± orthopyroxene)
2. Pelitic rocks:
   (a) cordierite-quartz-garnet-biotite (- sillimanite)
   (b) (sillimanite-cordierite-biotite)
   (c) (cordierite - orthopyroxene - quartz - biotite)
3. Quartzites:
   (a) quartz (- muscovite-sillimanite ± feldspar)
4. Metajaspilites:
   (a) quartz-magnetite-orthopyroxene ± garnet ± clinopyroxene (± hornblende)
5. Basic granulites:
   (a) plagioclase - clinopyroxene - orthopyroxene-hornblende (± biotite)
   (b) clinopyroxene - orthopyroxene - hornblende (± biotite)
   (c) orthopyroxene-hornblende (± spinel)

The appearance of orthopyroxene in rocks of basic composition is normally accepted as defining the lower boundary of the granulite facies; that is, in basic rocks the assemblage plagioclase - clinopyroxene - orthopyroxene - hornblende is diagnostic (Turner 1968, p. 320). Thus the ubiquitous occurrence of orthopyroxene in the basic granulites at Mt Bakewell shows that granulite facies conditions were attained. Coexistence of hornblende and orthopyroxene in textural equilibrium is a characteristic of the hornblende-granulite subfacies. In the plagioclase-bearing granulites the hornblende is the brown variety typical of the granulite facies, but in the plagioclase-free rocks it is green.

Evidence that load pressure during metamorphism was low is provided by the presence of cordierite in rocks of suitable composition (Turner 1968). De Waard (1965a) has suggested that cordierite breaks down under higher load pressures according to a reaction such as Cord → Alm + Sill + Qtz.

The mineral assemblages of the granitic gneisses at Mt Bakewell are common in both amphibolite and hornblende-granulite terranes. Binns (1964) and Buddington (1963, 1965) have shown that garnet develops in quartzo-feldspathic rocks as a result of increasing grade, and Turner (1968, p. 334) states that prevalence of garnet in quartzo-feldspathic rocks is characteristic of the granulite facies. De Waard (1965b), however, has stressed the importance of composition as an additional factor controlling the occurrence of garnet in quartzo-feldspathic rocks, garnetiferous rocks being higher in Al_2O_3 than nongarnetiferous rocks formed under the same conditions. At Mt Bakewell the appearance of garnet is believed to be a reflection of the high grade attained, but the presence or absence of garnet in the granitic gneisses within the area appears to be controlled by rock composition.

Orthopyroxene is widely developed in the metajaspilites as may be expected in the granulite facies. The quartzites, containing "primary", as well as retrograde, muscovite are, in view of the foregoing, somewhat anomalous because muscovite is foreign to the granulite facies. The reaction

$$\text{Musc} + \text{Qtz} \rightarrow \text{Sill} + \text{K-feld} + H_2O$$

is considered to occur under upper amphibolite facies conditions (Turner 1968, p. 320).

Thus within the small area studied assemblages characteristic of the granulite and amphibolite facies are intermingled, with hornblende-granulite subfacies assemblages predominant. This situation is typical of transition zones between amphibolite and granulite facies regions (de Waard 1965a) where physical conditions of metamorphism were presumably appropriate to the boundary between these facies. Such zones are now accorded transitional facies status: the amphibolite-granulite transitional facies (Turner 1968). The possibility that a regional gradation from amphibolite to granulite facies may be recognized in the Jimperding metamorphic belt will be considered later.

Retrograde effects, though common, are not intense and are normally clearly recognisable. In the granitic gneisses slight chloritisation of biotite is fairly common, and unstable relicts of hypersthene surrounded by anthophyllite were found in one specimen. Pinitisation of cordierite and replacement of sillimanite by muscovite are fairly common. In the basic granulites alteration of pyroxenes and hornblende to actinolite, chlorite, or talc is rare. Fringes of fibrous amphibole on orthopyroxene grains are very common in the metajaspilites, and in some specimens small unstable relicts of orthopyroxene are completely enclosed by grunerite aggregates.

Thus all the rock types found in the area show evidence of slight downgrading, involving development of minerals of the amphibolite and greenschist facies. These retrograde effects appear to be most extensively developed near dolerite instrusions, suggesting a direct relationship. Evidence of fairly extensive deuteric activity in some dolerites supports the conclusion that volatiles from the cooling magma probably catalysed retrograde reactions as well as providing new materials. However, retrograde reactions are not confined to dolerite contacts. Localised shearing has also initiated fairly strong downgrading. Less pronounced effects are uniformly distributed throughout the area, possibly as a result of tectonic movements, or simply readjustment of the rock during cooling in the presence of small amounts of water

The Original Rocks Prior to Metamorphism

1. *Granitic Gneiss*—There are at least three possibilities for the origin of the granitic gneiss:—

(a) It may be of igneous or meta-igneous origin, having been emplaced as large granite sills either before or after metamorphism.

(b) It may be the product of granitisation.

(c) It may be the result of recrystallisation of a quartzo-feldspathic sediment during regional metamorphism.

Various interpretations have been made concerning similar granitic gneisses occurring elsewhere in the Jimperding metamorphic belt. For example Prider (1944) believes that the granitic gneisses near Toodyay are of igneous origin, while Johnstone (1952) proposes a metasedimentary origin for those of the Hamersley Siding area, near Mt Bakewell.

At Mt Bakewell the following observations appear to be significant:—

(a) The gneiss is everywhere conformable with the quartzite which is an undoubted metasediment. These two rocks are commonly interbedded with one another over a thickness of a few feet at exposed contacts between them.

(b) Textures within the gneiss are not igneous, but crystalloblastic.

(c) Thin metasedimentary bands within the gneiss are reasonably continuous, an unlikely situation for xenoliths in an intrusive body.

(d) There is no textural or other evidence that metasomatic processes have widely contributed to the formation of the gneiss. Potassium feldspar showed corrosion boundaries in very few of the many thin sections examined. Furthermore, the metasediments interbedded with the gneiss show no sign of granitisation.

(e) The rounded nature of small grains of zircon and monazite is consistent with abrasion during a sedimentary cycle.

Thus the evidence does not support an igneous, meta-igneous, or granitisation origin, but it is consistent with a metasedimentary origin. If isochemical metamorphism is assumed, the original sediment was probably arkose or greywacke. The general abundance of microcline suggests a predominance of K_2O over Na_2O which, according to Pettijohn (1957) is a characteristic of arkose, but not of greywacke.

2. The *cordierite-bearing rocks* occur as small conformable lenses in the granitic gneiss. Their inferred chemical composition suggests that they represent pelitic lenses in the original quartzo-feldspathic sediment.

3. The *quartzites* are the product of regional metamorphism of fairly pure quartz sandstones. Most original clastic structures except bedding have been obliterated. Minor feldspar and very rare fragments of granitic rock appear to be of detrital origin and a small amount of clay in the original sediment has recrystallised to sillimanite and muscovite. The origin of chromium in the chrome-muscovite is not readily explained as there are no chrome-bearing detrital minerals present, and chromium-metasomatism arising perhaps from ultrabasic intrusions cannot be demonstrated by field relationships. Rounded grains of zircon and rutile are probably detrital. The needle inclusions of rutile in quartz are the result of exsolution of TiO_2, which was possibly originally derived from detrital rutile taken into solid solution during metamorphism.

4. The *metajaspilites*, from their composition (Table 1) and field occurrence (interbedded with metasediments) are considered to have been derived from iron-silica-rich sediments (e.g. Miles 1946). Metamorphism has destroyed all original sedimentary features except bedding (which is now preserved as mineralogical banding). Therefore the exact nature of the original sediment is not evident, but rocks of this type are usually considered to be derived from chemically precipitated iron-rich cherts (iron formation) in which the iron was present as an oxide (hematite, magnetite), carbonate (siderite, ankerite), or silicate (e.g. greenalite) depending largely on Eh and pH at the site of deposition (James 1954). Precipitation is likely to be a slow process occurring in very quiescent, possibly shallow, marine basins of restricted circulation, in the absence of an influx of detritus. Hence if the metajaspilites of Mt Bakewell are of chemical, rather than detrital, origin they must have been precipitated during temporary pauses in mechanical sedimentation of the arkose or greywacke (rocks usually characterised by rapid deposition) with which they were interbedded.

5. The *basic granulites*: Recrystallisation during metamorphism has destroyed the original textures, so field relationships and chemical composition are the only criteria that can be used to identify the parent rock. The basic granulites occur as conformable bands and lenses in the gneiss and therefore may be interpreted as sedimentary layers or intercalated basic sills or flows. The plagioclase-bearing granulites are chemically similar to basalt, basic tuff, and (in view of their high CaO content) impure limestone, whereas the less common granulites lacking plagioclase chemically resemble olivine basalt (Table 3) and impure dolomite.

The field relationships between the two varieties of granulite are not clear due to poor outcrop but they are commonly closely associated. Hence these rocks may be the products of differentiation in basic sills or flows; they may represent original variations in an impure carbonate sediment; or they may be the product of metamorphic differentiation of some appropriate rock. The first possibility is preferred.

6. The *ultrabasic rocks* occur as thin bodies conformable with the metasediments. The following problems must be considered:

(a) The nature of the original rock.

(b) The time of emplacement relative to folding and metamorphism.

(a) The nature of the original rock: Although discordant contacts have not been found, the ultrabasic rocks are believed to be of igneous origin because of their inferred chemical composition, the presence of occasional relict textures interpreted as being igneous in character, and the occurrence of enclosed blocks of granitic gneiss with the appearance of xenoliths. Derivation from an orthopyroxenite parent appears probable at one locality but normally remnants of the original minerals are not present and the relict textures do not permit reliable distinction between dunite, peridotite, pyroxenite, etc., so the identities of the original rocks remain uncertain.

(b) The time of emplacement: The ultrabasic rocks show varying degrees of alteration and deformation. The serpentinite with relict (igneous?) texture is undeformed, and talc rocks, which appear to have been derived without deformation from the serpentinite, grade laterally into slightly foliated tremolite-actinolite rocks (locally downgraded to chlorite + talc). These mineral assemblages are characteristic of the greenschist facies, and the ultrabasics therefore represent a much lower grade of metamorphism than the other rocks of the area. Two interpretations may be offered. Either the ultrabasics were (i) emplaced before the main metamorphic episode but have been extensively downgraded, or (ii) emplaced after the main phase of metamorphism.

The first possibility seems unlikely in view of the presence of relict textures of probable igneous character, and the complete absence of relicts of higher-grade metamorphic assemblages. Notwithstanding their probable high water content it is unlikely that the ultrabasics should experience such intense selective downgrading. It is more likely that they were emplaced after the highest metamorphic grade was attained, probably during waning metamorphism. Elkington (1963) reached a similar conclusion regarding the extensively altered bronzite peridotite body in a more northerly exposure of the Jimperding metamorphic belt at Nunyle. The ultrabasic rocks at Mt Bakewell and Nunyle are cut by, and therefore older than, the dolerite dykes.

7. *Original Tectonic Environment of Sedimentation.* Recognition of the original tectonic environment of sedimentation is difficult because metamorphism and deformation have obliterated sedimentary textures and structures, and left the original identity of some rock types in doubt. The question as to whether the granitic gneiss was derived from arkose or greywacke (rocks typical of contrasting tectonic environments) is of considerable importance with regard to the original environment of sedimentation, particularly as the granitic gneiss is by far the major component of the sequence. The original association in the Mt Bakewell area was possibly greywacke with minor shale lenses, quartzite, iron formation, and basic volcanics. Several similar Precambrian associations are known.

Pettijohn (1943) describes the association of greywacke, ophiolitic igneous material, minor slate, and thin, discontinuous lenses of iron formation from the Archaean of the southern Canadian Shield. This association, which lacks quartzite, he ascribes to a eugeosynclinal environment of sedimentation.

James (1954, 1955) describes the Upper Huronian section of northern Michigan which comprises mainly greywacke, slate, and basic volcanics, with fairly common conglomerate, quartzite, and iron formation. James believes that this association is eugeosynclinal, the iron formation having been chemically precipitated in shallow, restricted basins during periods of deep chemical weathering while clastic contributions to the basins were almost nil (James 1954, 1966) Periodic influx of clastic material, now represented by rocks such as greywacke and quartzite, represent intervals of structural disturbance during which chemical weathering became subordinate to physical disintegration of the land surface.

The lithological similarity of the Upper Huronian of northern Michigan and the Archaean of the southern Canadian Shield to the possible original association in the Mt Bakewell area suggests analogous tectonic environments of deposition. Hence the Mt Bakewell rocks may have been laid down during the eugeosynclinal phase of an orogenic cycle. Rapid clastic sedimentation, yielding greywacke, quartzite, and minor shale, predominated, but thin lenses of iron formation were chemically precipitated in restricted basins that were temporarily not receiving an influx of detritus.

Evidence that may be taken as contrary to the eugeosynclinal sedimentation hypothesis includes the possible, though rare, occurrence of current bedding in the quartzite, and the relatively restricted occurrence of basic volcanic material. If the granitic gneisses are meta-arkoses, rather than metagreywackes, a post-orogenic basin or fault trough environment seems more likely.

Structure

The structural interpretation is based on field observations only. Petrofabric work has not been attempted, but is strongly recommended as an avenue for further study. The structure of the area is complex, and interpretation is further complicated by the scarcity of minor structures to indicate facing in the succession and by the discontinuous nature of many distinctive marker bands, due both to original lensing and to boudinage during deformation. Lithologically distinctive units such as the ultrabasic rocks and basic granulites, though generally conformable with the metasediments and occupying reasonably consistent positions in the succession, are not reliable as markers because of their likely intrusive origin. The quartzite proved to be most valuable in determination of the structure. Due to its resistance to erosion, outcrop is almost continuous, and it contains significant features such as *b* - lineation, fracture cleavage, drag folds, and possible relict current bedding.

Folding

Three sets of folds have been recognised and these are believed to be the product of at least two, and possibly three, phases of folding. The following observations are significant in the determination of the major structure.

1. The foliation and original bedding are usually mutually parallel. From Mackies Siding west to the summit of Mt Bakewell (a distance of 2½ miles) the metasediments strike approximately W.-E. and dip gently north. At Mt Bakewell the strike swings northwards to NNW.-SSE. (dip ENE.) and continues thus for a further 2¼ miles.

2. Sillimanite, amphiboles, and micas commonly provide a mineral lineation with a fairly consistent NW.-SE. trend. Between Mt Bakewell and Mackies Siding the lineation plunges gently NW., but north and west of Mt Bakewell the plunge is normally to the SE., though reversals are common. It is believed that this is a *b* - lineation developed during the main period of metamorphism and deformation, and that it defines the major axis of folding.

3. Extended traverses normal to the regional strike encounter repetitions and reversals of the sequence without reversals of the dip.

4. Minor structures indicating facing in the succession are rare. On the SW. escarpment of Mt Bakewell drag folds in the quartzite at 010W, 160S (Fig. 3), and in the gneiss at 008W, 156S and 025W, 138S suggest overturning. The succession exposed on the northern dip-slope of Mt Bakewell appears to be right-way-up, suggested by drag folds in the gneiss at 092E, 090S, and by structures resembling relict current bedding in the quartzite at several localities.

From these observations it is concluded that the metasediments were initially folded isoclinally about axial planes striking NW.-SE. (parallel to the mineral lineation) and dipping

Figure 3.—Drag folding in quartzite at 010W, 160S, looking NW. The relationship between the drag fold axial planes and bedding planes (dip and strike indicated by clinometer arms) suggests the overturned limb of a recumbent isoclinal fold.

gently NE. A generalised reconstruction of the isoclinal folding is presented in Figure 4. Mt Bakewell is the surface expression of an anticline, overturned to the SW. and almost recumbent. The other folds illustrated in Figure 4 are not certain.

The present curvature of the axial surface traces and the change of the regional strike at Mt Bakewell from W.-E. to NNW.-SSE., accompanied by reversal of the *b*-lineation plunge from NW. to SE., are interpreted as the results of superimposed warping of the isoclinal folds into a broad NE.-plunging synform. This warping may have been synchronous with the isoclinal folding.

Minor open concentric folding about axes trending E.-W., associated with steeply dipping, E.-W.-striking fracture cleavage, is evident in the quartzite at many localities throughout the area (Fig. 5). This folding has warped the mineral lineation described previously, and therefore occurred after the isoclinal folding and metamorphism, probably at a time when the rocks were in a relatively more brittle state.

The fold systems described above are believed to represent successive deformation phases of a single orogenic cycle, rather than unrelated events.

Faulting

Small shear zones dipping gently NE. occurring in the axial region of the anticline at Mt Bakewell suggest minor thrusting along the nearly recumbent axial plane during isoclinal folding. The association of retrograde metamorphism with these shear zones in turn suggests that isoclinical folding movements may have continued after the period of maximum metamorphic intensity.

The presence of minor nearly vertical faults trending approximately NW.-SE. is suggested by several narrow silicified brecciated zones in the SW. part of the area. The direction of movement is generally not evident, but at O34W,

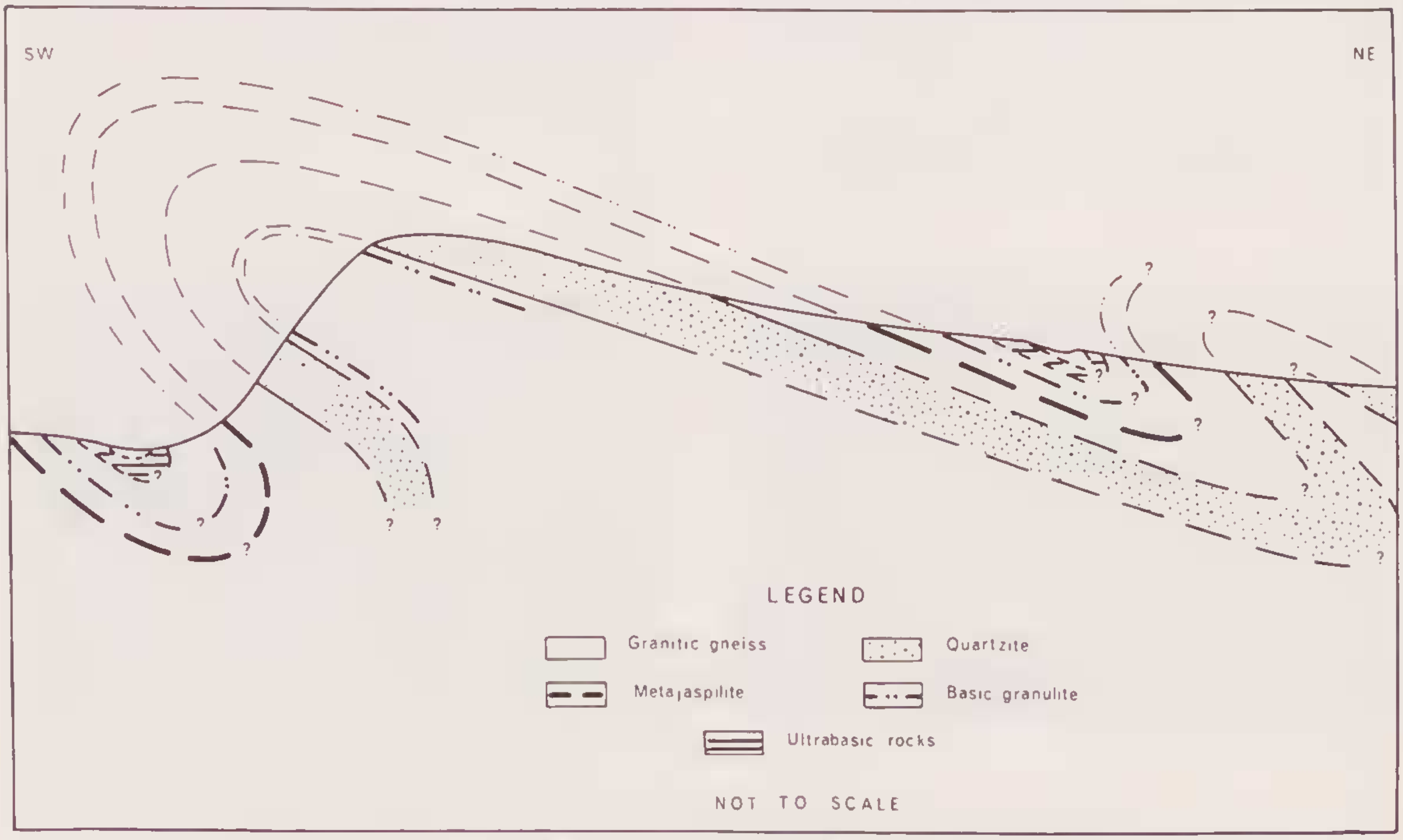

Figure 4.—Generalised reconstruction of isoclinal folding at Mt Bakewell.

123S drags in the gneiss suggest north block relatively upwards. The displacement is probably not large. At least some of the high-angle faulting post-dated dolerite intrusion.

Regional Considerations

Wilson (1958) has defined an area in the Wheat Belt region of southwestern Australia in which granulite facies rocks are exposed. The western boundary of this area is a NNW.-trending line through the Bolgart, Northam, York, and Brookton areas separating the high-grade (granulite facies) rocks to the east from the medium-grade (amphibolite facies) rocks to the west. The suggestion by Wilson that this boundary may be a major fault is strongly supported by geophysical evidence. A zone of active seismicity, known as the Yandanooka-Cape Riche Lineament, follows the boundary along a SSE. projection of the Urella Fault to Cape Riche (Everingham 1966). Since this boundary (fault?) passes close to Mt Bakewell an examination of the nature of this change in metamorphic grade is pertinent to this paper. If the increase in grade is sharp it seems likely that the higher-grade rocks may have been considerably uplifted into juxtaposition with the lower-grade rocks to the west. Alternatively, if a gradual increase in grade from west to east is discernible, the fault may not be entirely responsible for the surface exposure of the granulites.

On the basis of field observations and a survey of relevant literature the author believes that the Jimperding belt exhibits a pronounced progressive increase in metamorphic grade from west to east. Pelitic and basic rocks were found to be the most useful indicators of grade, and these have been used to establish three zones, which are most fully exposed along the latitude of Toodyay. The grade increases from Zone A in the west to Zone C in the east (Fig. 1).

The exposures of the Jimperding metamorphic belt west of Jimperding Brook comprise Zone A. Here pelitic rocks have recrystallised to quartz-biotite-muscovite schists in which the more aluminous bands may contain abundant andalusite. Of the other index minerals staurolite and kyanite are absent, whereas garnet and sillimanite are very rare. Basic rocks of this zone contain blue-green hornblende, sodic plagioclase and minor quartz, epidote, and sphene. Clinopyroxene is a possible additional constituent.

In Zone B andalusite disappears and sillimanite becomes common in pelitic rocks, whereas basic rocks are similar to those of Zone A. Zones A and B belong to the amphibolite facies.

The western margin of Zone C, the highest grade zone, is defined by the appearance of orthopyroxene in rocks of basic composition. More or less coincident with the appearance of orthopyroxene are the disappearance of sphene and epidote, the change in colour of hornblende from green to brown, and a change in the composition of plagioclase to andesine or labradorite. Thus the typical basic assemblage becomes plagioclase-orthopyroxene-clinopyroxene-hornblende. Pelitic rocks in Zone C usually contain cordierite, quartz, feldspar, garnet, biotite, and sillimanite in various combinations. Muscovite is absent. The Mt Bakewell area lies in Zone C close to the orthopyroxene isograd.

The orthopyroxene isograd marks the *first* appearance of orthopyroxene in *basic* rocks. However, orthopyroxene occurs in metajaspilites and rocks related to cordierite-anthophyllite rocks in Zone B within about 2 miles of the orthopyroxene isograd, and basic rocks lacking orthopyroxene may be found in Zone C near the isograd. Hence it appears that the boundary between Zones B and C (the amphibolite-granulite facies boundary) is somewhat gradational. The orthopyroxene isograd appears to coincide with the western margin of the fault zone associated with the Yandanooka-Cape Riche Lineament, and it is possible that granulite facies rocks have been brought closer to the surface by uplift of the eastern block. However, since it is believed that a fairly gradual lateral transition from amphibolite

Figure 5.—Crossfolding of quartzite bedding. A.—Looking west at 025W, 059S, where the regional dip is ENE (towards the observer). Two sets of fracture cleavage are evident. One, parallel to the clinometer and the mineral lineation, is vertical and strikes 310°. The other, parallel to the hammer handle and the axis of crossfolding, dips 70°S and strikes 270°. B.—Looking east at 030E, 125S, where the regional dip is towards the north.

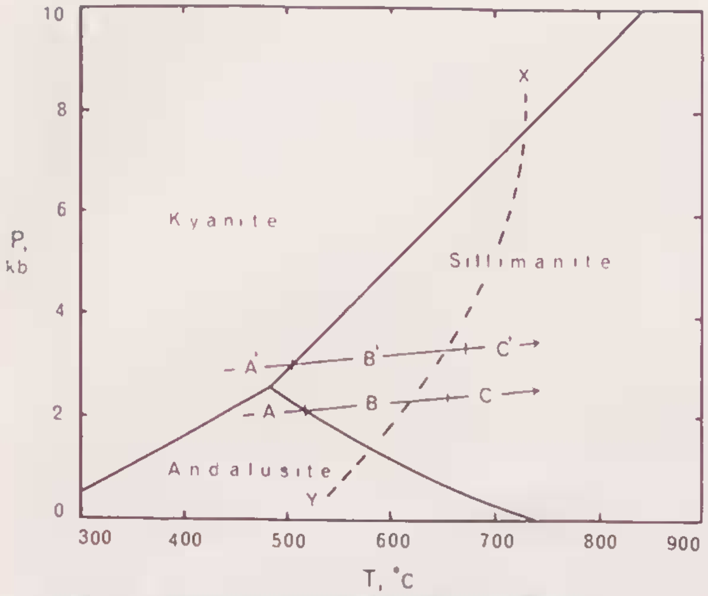

Figure 6.—Aluminium silicate phase diagram and the curve (XY) of univariant equilibrium for musc + qtz $\rightleftharpoons$ K-feld + Al_2O_3 + H_2O, both as preferred by Turner (1968). The line ABC represents the likely conditions of metamorphism in Zones A, B, and C along the latitude of Toodyay. The line A'B'C' may be a closer approximation to the conditions in certain areas south of Toodyay. The boundary between Zones B and C (the orthopyroxene isograd) is drawn somewhat arbitrarily, but it should lie on the high-temperature side of the curve XY. Binns (1964) has estimated that the orthopyroxene isograd at Broken Hill represents about 750°-800°C, but the occurrence of muscovite in quartzite suggests a slightly lower value at Mt Bakewell.

facies in the west to granulite facies in the east is recognisable, the fault is probably not alone responsible for the exposure of the higher-grade rocks.

The likely P-T conditions of the three zones described above can be represented on the aluminium silicate phase diagram by the line ABC in Figure 6. The occurrence of andalusite in Zone A and cordierite in the higher-grade zones suggests that pressure during metamorphism was relatively low. Indeed the sequence of zones is comparable with the andalusite-sillimanite type of metamorphic facies series which is considered by Miyashiro (1961) to be indicative of low pressure.

A variation from the sequence of zones described above is suspected in the Jimperding belt south of Toodyay. Zone A cannot be traced very far to the south as it is truncated by a large granite batholith. However, the pelitic rocks in Zone B immediately east of this batholith in places contain minor kyanite in addition to sillimanite (Simpson 1936, Johnstone 1952) whereas andalusite is absent. The persistence of kyanite instead of andalusite in the sillimanite zone is typical of the andalusite-sillimanite facies series, and suggests that south of Toodyay the pressure during metamorphism was higher than further north (Fig. 6). Structural evidence in the Jimperding metamorphic belt supports the suggestion that the occurrence of kyanite in preference to andalusite is a consequence of higher pressure, since andalusite occurs only in the regions where the folding is relatively open, whereas kyanite appears in more tightly folded rocks. Unfortunately, owing to extensive encroachment by a granite batholith upon the lower-grade metamorphic zones, the distribution of kyanite and andalusite is not sufficiently well known to determine whether pressure varied in an irregular manner or increased progressively from north to south. In any case the Jimperding metamorphic terrane exhibits some of the characteristics of the kyanite-sillimanite facies series as well as those of the andalusite-sillimanite series, and is therefore comparable with the low-pressure intermediate series of Miyashiro (1961).

To summarise, it appears that at least three zones representing progressive increase in grade of regional metamorphism from west to east can be recognised in the Jimperding belt, and that temperature was the major factor controlling the grade. In addition, variations in pressure controlled the occurrence of andalusite or kyanite in the lower grades. It must be stressed that the zonal sequence outlined above is proposed somewhat tentatively. Further detailed work is necessary to establish this sequence and it is likely that additional isograds may be recognised.

Igneous Rocks

Petrography

1. The *adamellite* (50520) is a fine-, even-grained rock with allotriomorphic granular texture, and shows little petrographic variation. Plagioclase, microcline, and quartz in sub-equal amounts are the major constituents. Plagioclase is oligoclase-andesine, normally zoned from An_{16} (margin) to An_{42} (core), and twinned on the albite and pericline laws. Alteration to saussurite and sericite is moderate and some grain margins are myrmekitic. Microcline is crosshatched and weakly perthitic. Scattered flakes of biotite (X = light brown, Y = Z = dark brown) constitute about 5% of the rock. Minor accessories include euhedra of pyrite, apatite, zircon, and sphene.

2. *Dolerite.* The proposed classification of the numerous dolerite intrusions has been outlined in the General Geology section. The various types are described below.

(a) The *altered quartz dolerite* (50522) is a holocrystalline, medium-, even-grained greenish grey rock with subophitic texture. Subhedral plagioclase is almost completely altered to saussurite, sericite, and chlorite. The pyroxene is pale pinkish augite with β = 1.696 and $2V_z$ = 48°, indicating an average composition of about $Ca_{40}Mg_{38}Fe_{22}$. Pigeonite is very rarely present and orthopyroxene has not been observed, although the appearance of some partially altered pyroxene grains suggests that cores and exsolved plates of a calcium-poor phase may have been preferentially altered. Hornblende (X = straw, Y = brown, Z = dark yellowish green) occurs as reaction rims on augite and as rare discrete grains. Biotite (X = straw, Y = Z = dark brown), occurring as clustered flakes and reaction rims on hornblende, is a minor constituent of some specimens (e.g. 50523). Fibrous uralite (X = yellow, Y = green, Z = bluish green) and pale green chlorite are abundant marginal alteration products of pyroxene and hornblende. Secondary epidote is fairly common. Interstitial micropegmatitic quartz-orthoclase intergrowths constitute about 5% of the rock. Ilmenite and magnetite are common accessories, whereas apatite and pyrite are fairly rare.

(b) The *quartz-orthopyroxene dolerite* (e.g. 50524) has a similar appearance and texture to the altered quartz dolerite. The plagioclase is subhedral andesine-labradorite, normally zoned from An_{43} (margin) to An_{60} (core). The dominant pyroxene is pale pinkish brown augite with variable composition, as indicated by the range of $2V_z$ from 33° to 51°. A $2V_z$ variation of up to 12° has been recorded from single specimens, but the normal value is about 46°, with $\beta = 1.696$, suggesting an average composition of $Ca_{38}Mg_{39}Fe_{23}$. Subordinate amounts of pigeonite ($2V_z = 0° - 10°$; rarely with (001) exsolution lamellae), commonly enclosed by augite, occur in many specimens. In most samples examined orthopyroxene is present, constituting up to 30% (commonly about 10%) of the total pyroxene content. The orthopyroxene is bronzite (about Fe_{27}, with $\gamma = 1.698$, $2V_x = 66°$), and usually forms discrete subhedral grains extensively replaced by chlorite and minor talc (e.g. 46293, 46297). Rarely (e.g. 34475) it occurs as irregular patches enclosed in pigeonite, suggesting that in some rocks at least, the orthopyroxene is the product of pigeonite inversion. Hornblende, biotite, and iron ores have similar properties and occurrence as in the altered quartz dolerite. Minor interstitial quartz and micropegmatite occur in most samples. Apatite and pyrite are rare. Alteration of plagioclase to saussurite, and clinopyroxenes to uralite and chlorite is much less intense than in the altered quartz dolerite but localised epidotisation may be very strong.

The *basaltic plagioclase-augite-phyric dolerite* (50528, 50529) is a black rock with an aphanitic groundmass enclosing phenocrysts of plagioclase and augite. The phenocrysts, which constitute 15-25% of the rock, form subophitic aggregates to give a glomeroporphyritic texture. The plagioclase is subhedral labradorite-bytownite, normally zoned from An_{60} (margin) to An_{75} (core). The augite is subhedral to anhedral, with $\beta = 1.696$, $2V_z = 48°$ indicating $Ca_{40}Mg_{38}Fe_{22}$. Pigeonite and orthopyroxene have not been identified. The groundmass is composed of very fine laths of plagioclase with intergranular pyroxene and iron ore. Glass was not observed.

(c) The *basaltic plagioclase-phyric dolerite* (50531, 50532) is composed of microscopic phenocrysts of plagioclase (labradorite: normally zoned from An_{51} (margin) to An_{63} (core)) in an aphanitic groundmass of plagioclase laths with intergranular pyroxene (augite?) and iron ore. Phenocrysts of augite are rare, olivine very rare. Pyrite spheroids about 2 mm in diameter are abundant in some samples. Alteration of augite to chlorite is not unusual. Glass occurs in some specimens.

Petrogenesis

1. The *adamellite* dykes have sharp discordant margins suggesting intrusive emplacement. Radiometric Rb-Sr dating has shown that they are approximately the same age (about 2,800 m.y.) as the regional metamorphism in the area (Martin 1961). The dykes are probably related to the large, apparently intrusive, adamellite batholith outcropping about 4 miles west and south of Mt Bakewell, and they may represent a more mobile fraction of a large amount of palingenetic magma generated during regional metamorphism. Emplacement probably occurred during the closing stages of the orogeny.

2. *Dolerites.* The order of emplacement of the various dolerite intrusions has been stated in the section dealing with General Geology. Lack of metamorphic effects in the dolerites suggests that emplacement post-dated regional metamorphism, though it is admitted that alteration in the quartz dolerites may be due to weak metamorphism. The following section briefly mentions some aspects of the cooling history of the rocks, and suggestions regarding tectonic control of emplacement are made.

(a) The *altered quartz dolerite*:— The petrography of these rocks suggests that they have tholeiitic affinities, and the presence of normative hypersthene and very minor normative olivine (Table 4) places them close to saturated tholeiite (after Yoder and Tilley 1962). Due to extensive alteration little can be said regarding the cooling history of the pyroxenes. The only fresh pyroxene present in most specimens is augite but textures suggest that a calcium-poor phase occurring as cores and exsolved plates in the augite may have been preferentially replaced by uralite and chlorite. The hornblende and biotite appear to be of late magmatic origin and the micropegmatite is the result of late crystallisation of an acid residuum. The alteration of plagioclase and pyroxene is probably deuteric.

Most of the altered quartz dolerite dykes trend NNW.-SSE. parallel to the dominant tectonic trend throughout most of the West Australian Precambrian shield. The factors controlling emplacement of these intrusions are not known; the preferred trend is not easily related to tension zones associated with fold structures in the surrounding rocks.

(b) The *quartz-orthopyroxene dolerites* are petrographically tholeiitic, and because of the presence of normative quartz and hypersthene (Table 4) may be classified according to Yoder and Tilley (1962) as oversaturated tholeiites.

The occurrence of orthopyroxene, pigeonite, and augite together is interesting, but the available evidence concerning the pyroxene crystallisation history is somewhat inadequate and contradictory. The chilled marginal facies of these intrusions contains augite as the only phenocrystal pyroxene, which may suggest that augite was the first pyroxene to crystallise. In contrast, grain relationships in the cores of the intrusions (which are chemically similar to the margins—see Table 4) strongly suggest that calcium-poor pyroxene began to crystallise before the augite. The original identity of the Ca-poor phase—whether orthopyroxene or pigeonite—is also in doubt. In some rocks orthopyroxene occurs as small, diffuse and irregular patches in pigeonite, suggesting that the original Ca-poor pyroxene was pigeonite which has undergone incipient inversion to orthopyroxene. However, in the cores of large intrusions orthopyroxene occurs as discrete prismatic grains and pigeonite is very rare. Here the orthopyroxene may be primary, having crystallised instead of pigeonite at a temperature below the inversion curve (Brown 1957, Fig. 5). This suggestion is supported by a comparison of the orthopyroxene composition (about Fe_{27}) with Brown's data. Alternatively the orthopyroxene may be the result of complete inversion of original pigeonite during slow sub-solidus cooling. The exsolution textures normally associated with inverted pigeonite are not evident, but extensive alteration precludes a confident statement to the effect that the orthopyroxene is primary.

As in the altered quartz dolerite, hornblende and biotite are late magmatic, and the micropegmatite represents a final acid residuum. Deuteric effects are much less pronounced than in the altered dolerite, suggesting that the quartz-orthopyroxene dolerite magma possessed a lower volatile content.

The quartz-orthopyroxene dolerite dykes normally trend about NW.-SE., but they swing locally to a W.-E. trend, parallel to a fracture cleavage well developed in the country rocks, as they cross tension zones associated with pre-intrusion W.-E. crossfolding (see Geological Map).

The magnetic polarity of these rocks has been studied by Gregson (1961) who concluded that lightning strikes were responsible.

The *basaltic plagioclase-augite-phyric dolerite* intrusions are petrographically and chemically (Table 4) identical with chilled margins of the quartz-orthopyroxene dolerite dykes and the author agrees with Martin (1961) that these rocks are comagmatic. Field evidence supports this conclusion.

(c) The *basaltic plagioclase-phyric dolerites* occur as small rapidly chilled tholeiitic intrusions that were emplaced both before and after the two major varieties of dolerite (cf. Martin 1961). The chemical analysis of a sample of this rock type quoted from Martin (1961) in Table 4 shows (with the exception of the SiO_2 content) similarities to the analysis of altered quartz dolerite, but a genetic relationship has not been established.

Summary of Conclusions

The geology in the Mt Bakewell area is similar to exposures of the Jimperding metamorphic belt elsewhere. Granitic gneisses, cordierite-bearing rocks, quartzite, metajaspilite, and basic granulites are the products of Early Precambrian syntectonic high-grade regional metamorphism of a deeply buried sedimentary sequence which included arkose or greywacke with shale lenses, quartz sandstone beds, thin bands of iron formation, and intercalated basaltic sills or flows. Isoclinal folding about axes trending NW.-SE. accompanied metamorphism and produced, at Mt Bakewell, a nearly recumbent anticline whose axial plane dipped to the NE. Superimposed warping of the isoclinal folds has resulted in a broad NE.-plunging synform.

TABLE 4

Chemical analyses and norms of dolerites from the Mt Bakewell Area (Quoted from Martin 1961)

	44596	34475	34495	34480	34487
SiO_2	47·97	49·68	49·75	49·76	52·52
TiO_2	2·06	0·88	1·13	1·15	1·56
Al_2O_3	14·88	13·91	14·59	14·57	16·47
Fe_2O_3	2·69	2·25	1·10	1·12	1·90
FeO	11·89	9·59	10·56	10·42	9·72
MnO	0·16	0·14	0·14	0·14	0·14
MgO	4·46	7·67	7·34	7·33	4·94
CaO	9·07	11·55	11·59	11·60	8·92
Na_2O	2·29	1·72	1·72	1·72	2·42
K_2O	1·93	0·13	0·26	0·26	0·26
H_2O^+	1·89	1·90	1·49	1·30	0·47
H_2O^-	0·06	0·16	0·15	0·26	0·26
P_2O_5	0·79	0·10	0·09	0·10	0·10
S	0·27	0·25	0·23	0·22	0·19
	100·41	99·93	100·14	99·95	99·87
C.I.P.W. Norms :					
Q		2·7	1·3	1·0	7·4
or	11·4	0·8	1·6	1·6	1·6
ab	19·4	14·5	14·5	14·5	20·5
an	24·6	29·9	31·3	31·3	33·3
di	12·1	22·4	21·1	21·4	8·6
hy	19·6	22·4	24·3	24·9	21·4
ol	0·8				
mt	3·9	3·3	1·6	1·6	2·7
il	3·9	1·7	2·1	2·2	3·0
ap	1·9	0·2	0·2	0·2	0·2
py	0·5	0·5	0·4	0·4	0·3

44596	Altered quartz dolerite.
34475	Quartz-orthopyroxene dolerite.
34495	Chilled margin of quartz-orthopyroxene dolerite.
34480	Basaltic plagioclase-augite-phyric dolerite.
34487	Basaltic plagioclase-phyric dolerite.

Analyst : I. D. Martin.

The mineral assemblages at Mt Bakewell are predominantly characteristic of the granulite facies, but intermingled amphibolite facies assemblages suggest that conditions of metamorphism were close to the amphibolite-granulite facies boundary. On a regional scale a progressive increase in metamorphic grade from west to east is evident, and Mt Bakewell lies in the transition zone between amphibolite and granulite facies rocks. Thus the rocks of the area are best assigned to the amphibolite-granulite transitional facies of Turner (1968). Minor retrograde effects are widely developed.

The following events occurred during the waning stages of orogeny:—

(i) Emplacement of palingenetic adamellite magma probably generated at a lower level in the crust during orogeny.

(ii) Emplacement of conformable ultrabasic intrusions at a time when greenschist facies conditions prevailed.

(iii) Mild crossfolding on E.-W. axes.

There is insufficient evidence to place these three events in correct chronological order.

Intrusion of tholeiitic magma took place after regional metamorphism and emplacement of adamellite and ultrabasic rocks, and occurred in at least three main phases in the following order: (i) altered quartz dolerite, (ii) quartz-orthopyroxene dolerite and related basaltic plagioclase-augite-phyric dolerite, (iii) basaltic plagioclase-phyric dolerite. Intrusion of altered quartz dolerite may have preceded E.-W. crossfolding but emplacement of the other dolerites occurred after crossfolding.

Minor high-angle faulting is the last recognisable event in the area prior to a long period of erosion, followed by formation of Tertiary laterite, followed in turn by further erosion to the present topography.

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Royal Society Medallist 1970

R. T. Prider

Professor Rex T. Prider was born at Narrogin, and received his schooling there and at Bunbury High School. He graduated with First-Class Honours in Geology from the University of Western Australia and received his Ph.D. from Cambridge University. Professor Prider joined the staff of the Geology Department at the University of Western Australia as an assistant lecturer in 1934, and was appointed as lecturer in 1939 and Professor (at the age of 38) in 1949. His department has established an enviable reputation throughout Australia and overseas for the high calibre of geologists that it has produced.

Professor Prider joined the Royal Society in 1931, and he has a distinguished record of service to the Society. He was secretary from 1939 to 1942 and has been a council member almost continuously since then, apart from brief absences when on sabbatical leave. He has twice been president, in 1944-45 and 1959-60. Professor Prider has also served as President of the Geological Society of Australia, President of Section C of A.N.Z.A.A.S., Federal President of the Gemmological Association of Australia, and as a member of the Advisory Council of C.S.I.R.O. He is currently Chairman of the Research Committee of the Water Research Foundation of Australia (W.A. Branch), an editorial advisor for the Geological Society of Australia and a member of the State Committee of C.S.I.R.O.

Professor Prider is the author of many important publications dealing with the geology of Western Australia, and is most renowned for his petrological and mineralogical studies, especially those dealing with the leucite lamproite volcanics of the West Kimberley district.

Professor Prider is one of the most distinguished geologists Western Australia has produced. The award of the Royal Society's Medal for 1970 is made in recognition of his services to geology and to the Society.